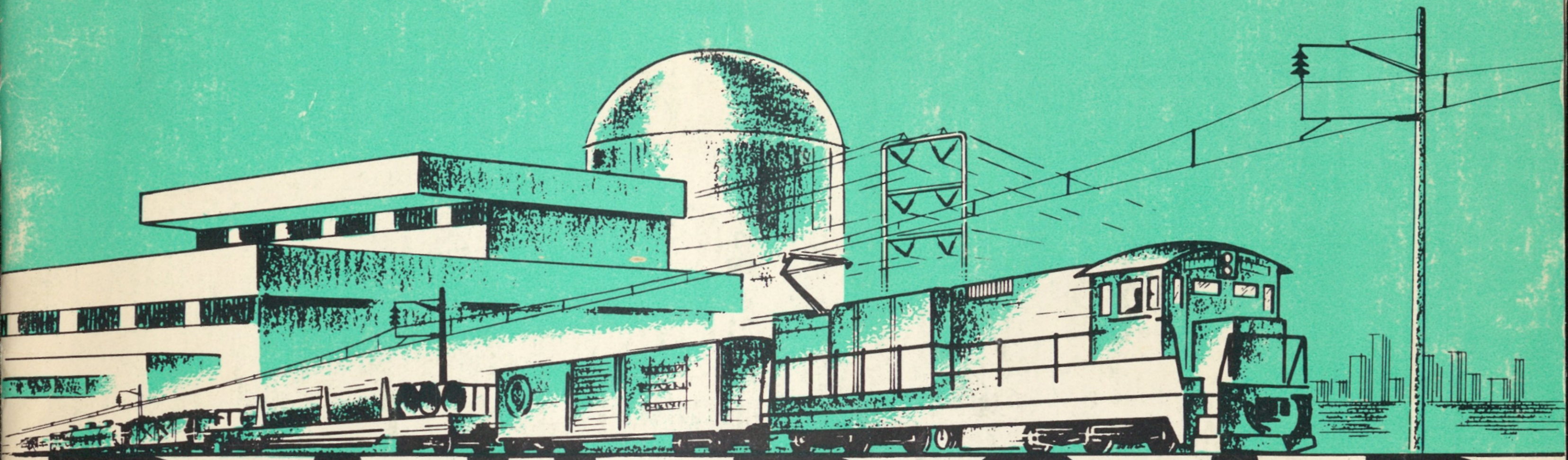

# RAILROAD ELECTRIFICATION

A Report to the Railroad Electrification Committee of Edison Electric Institute



*Volume 1*

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## A Report to the Railroad Electrification Committee of Edison Electric Institute

EDISON ELECTRIC INSTITUTE, 750 Third Ave., New York, N. Y. 10017

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# Contents

# Foreword

Early in 1965 the Board of Directors of the Edison Electric Institute appointed a committee to investigate the technical and economic feasibility and problems associated with electrification of railroads. A Task Force was organized to help carry out the assignment. The study was to include a review of the ability of power systems to supply single-phase energy for railroad propulsion directly from commercial-frequency electric power systems.

From experience abroad and, to a limited extent, in the United States, it appeared that economic advantages could accrue to both railroads and utilities by electrification. For the railroads, savings in investment costs and in operation and maintenance expenses may be available to railroad operators where traffic density is high and in other circumstances. For electric utilities, increased sales of power and energy provide incentive for investigation.

The Task Force felt that a complete study which would produce meaningful results could be made only if an operating high-traffic-density railroad were to be used as a model. The New York Central Railroad from Harmon, New York, to Cleveland, Ohio, was selected for this purpose. The route has a common terminal with the already electrified 600 route miles of the Pennsylvania Railroad and would add another 600 miles of electrified mainline railroad. (At the time, the two railroads were under separate management, but through a subsequent merger both are now operating as the Penn Central Company.)

A New York Central Railroad Electrification Engineering Study Group was organized in August 1966, with representation from the railroad and from each utility system involved. The engineering report of the Study Group was completed in January of 1969 (Volume 2 of this report).

In parallel with this work, Gibbs & Hill, Inc., was engaged by EEI to prepare designs and estimates for overhead wire systems using the latest technology available both in the United States and elsewhere (Volume 3 of this report).

It is hoped the information in this report will encourage railroads and electricity suppliers to review their respective systems to determine the financial and operating benefits to be realized from electrification.

Electrification of mainline railroads offers many advantages and should be vigorously pursued.

**The Task Force on Railroad Electrification**

E. B. SHEW, *Chairman,* Philadelphia Electric Company
P. A. DUKER, The Detroit Edison Company
R. P. O'BRIEN, Southern California Edison Company
B. A. ROSS, American Electric Power Service Corporation
F. S. WALTERS, Potomac Electric Power Company
R. W. WYMAN, The Cleveland Electric Illuminating Company

# Introduction

American electrified railroad operation began in 1888 when the first successful trolley line went into operation in Richmond, Virginia. From that date, street railway systems grew at a steady pace until in 1917 there were over 44,000 miles of electrified trolley track in operation. The success of electric traction could not be overlooked by the steam railroads as they sought the most economical motive power available, a search which continues with even greater intensity today.

The earliest electrified mainline railroad was placed in service by the Baltimore and Ohio Railroad shortly before the turn of the century. It operated with a trolley contact voltage of 600 volts d-c. This was copied directly from the trolley car and, in fact, the term "trolley wire" is still informally applied to a railway's overhead wire system.

In order to decrease the number of substations required to serve railways, the direct-current voltage was raised with subsequent electrifications. By 1915 the Chicago, Milwaukee & St. Paul Railroad was operating at 3000 volts d-c. In 1907 the first alternating-current system using 25-cycle, 11-kv, single-phase was placed in operation from New York to Stamford on the New York, New Haven & Hartford Railroad. In 1915 a similar electrification from Philadelphia to Paoli on the Pennsylvania Railroad was placed in service. In these cases, alternating current was selected to avoid the multiplicity of expensive converter stations and to take advantage of higher voltages. Twenty-five cycles was chosen rather than 60 since series-wound a-c traction motors had an insurmountable commutation problem at 60 cycles which could be solved at 25 cycles. Both the d-c and a-c systems operated successfully and electrification of mainline railroads reached a maximum of over 2400 route miles by 1938.

Since 1938, there has been no further expansion of electrified trackage in this country. In fact, several railroads abandoned electrification with the advent of the diesel locomotive. Justification for the decision was not clear in many cases.

Both the 25-cycle a-c and the d-c systems require conversion apparatus. Either rectifiers or motor-generators are needed with the d-c system, and frequency chargers (which are actually m-g sets) are necessary for the 25-cycle a-c system. The costs associated with owning, maintaining, and operating this special apparatus must be reflected in the cost of supplying electric energy. This can have the effect of increasing costs to a point where the inherent economic advantages of electrification suffer when compared to diesel operation.

With the development and successful operation of a rectifier-type locomotive, it is possible for 60-cycle power to be taken directly from commercial-frequency systems, thus avoiding the need for expensive and inefficient conversion apparatus and enhancing the economic advantage of straight electric operation. A simple transformation is all that is required to adapt the utility transmission line voltage to the appropriate railway "trolley" voltage. The modern electric locomotive uses d-c traction motors of the type used on the diesel-electric locomotive and on-board a transformer and rectifier are used to feed the traction motors.

The ability of modern electric power systems to withstand the unbalance resulting from a single-phase load has been greatly improved in recent years by increased capacity of individual systems and their interconnections. Where oil is the only fuel that can be used economically for a diesel locomotive, there are five types of fuel in current use as prime energy for electric power systems. This could be an important consideration in a national emergency when oil supplies may be reduced or diverted to defense activities. The growing concern over environmental quality and increasing demands for more effective controls in combustion processes may provide railroads with an opportunity to concentrate fuel conversion and air pollution control at a fewer number of points where more efficient and effective control procedures may be implemented.

In 1969, American Electric Power Corporation placed the automated Muskingum Electric Railroad in operation. This is a 15-mile coal-hauling line, which is operated at 25 kv, 60 cycle, single phase, and is the first commercial-frequency electrified railroad to operate in the United States. It has demonstrated the practicability of this type of railroad propulsion power.

While considerable interest in electrification has been expressed recently among North American railroads, no commitments have been made. On the other hand, there has been a large amount of progress made in foreign lands, notably in Great Britain, France, Japan, Norway, Germany, and India. Foreign operators repeatedly mention the superior economy of straight electric operation. Some have pointed to increased traffic on a branch as a result of electrification.

One foreign operator stated that: "At the moment the modern railbourne traction vehicle is the surest

and cheapest means of transport." This is just as true in this country where the cost ratio of rail, truck, and air transportation of freight is 1:5:15.

As the population of the nation increases and as railroad mergers are consummated, several high-traffic-density rail corridors have been developing. Moreover, the amount of freight hauled by rail is growing as improved shipping methods are developed. The trailer-on-freight-car concept, the automobile rack car, and the special-purpose jumbo freight car are among the innovations which have won some freight traffic back to the rails.

High-density rail lines can justify electrification to realize increased speed, improved economy, high reliability of the locomotive, and such intangibles as clean and quiet operation.

# Summary and Conclusions

- Electrification can be desirable from the railroad point of view.
- Electrification of high-traffic-density rail routes may produce important economic and service benefits to the railroad.
- Electrified railroad load is desirable from the utility viewpoint.
- Large modern electric power systems can successfully supply single-phase energy at commercial frequency for railroad propulsion.
- Railroad electrification is desirable from a national viewpoint.
- Electrified railroads contribute to the economic well-being of the areas served.
- Electrified railroads aid in more efficient use of land, particularly important in densely populated areas.
- A major deterrent to electrification is financing for the overhead wire system and wayside substations.
- Electricity supply to a mobile load of a single customer by multiple electric utility companies poses tariff and legal complexities not previously encountered by American utilities.
- The technology, equipment, ingenuity, and economic advantages for electrifying mainline railroads in this country are all at hand. A joint venture between a railroad and appropriate utility system operators is all that is needed for electrified railroad transportation to become a reality.

# Chapter 1

# Benefits to Railroad Economy and Operation

The benefits of straight electric locomotives are numerous and a meaningful comparison with diesel operation involves a detailed analysis. However, there are certain guidelines which may be helpful in approaching a study of electrification of specific railroads.

Benefits of electrification to the management and operation of a railroad may be divided into three categories, i.e., reduced investment and maintenance, improved service, and civic and social values.

## REDUCED INVESTMENT AND MAINTENANCE

Operation of an electrified railroad requires a new approach to scheduling, maintaining, and assigning equipment in order to realize maximum benefits of this type of propulsion power. A few of the more important economic advantages of electrified operation are given here; most can be evaluated with a substantial degree of accuracy. Care must be taken, however, to include all the economic factors applicable to each item.

Whether rolling stock is leased or owned by a railroad, its use factor, reliability, economic life, and operation and maintenance costs have a direct bearing on the earnings of the enterprise. The items listed below are not necessarily complete nor is it claimed all will apply to every railroad, but all should be examined thoroughly to determine the extent to which those applicable will contribute to the economic health of the operation under study.

1. The electric locomotive has an economic life about double that of the diesel.

Assuming a 15-year life for diesel locomotives and 30 years for straight electrics, a new diesel must be furnished at year 15 at a cost substantially higher (perhaps as much as 30 to 40 percent) than the one being retired. This is in addition to the more rapid amortization rate of the diesel due to its shorter life and is reflected in the lease payments or in cost of capital.

2. It is expected a straight electric locomotive will cost less than a comparable diesel.

Locomotive builders estimate a straight electric should cost about 85 percent that of a diesel on an equivalent rail horsepower basis.

3. Fewer electric locomotives are needed to do the same jobs.

It should be recognized only about 85 percent of a diesel-engine output is available at the rail. In contrast, the electric provides almost 100 percent of its horsepower at the rail—and even more for short periods of time.

Two 3,000-hp diesels will not quite do the job of one 5,000-hp straight electric; if the short time overload capability is used, three diesels would be needed in high-speed service.

Locomotive designers have expressed a belief that diesel locomotives will probably not be practicable above 6,000 hp or about 5,100 hp at the rail. On the other hand, straight electric locomotives can be built to deliver up to at least 10,000 hp at rail.

4. Electric operation means better equipment utilization.

Turnaround time is less for a straight electric locomotive. There is no filling of fuel tanks or inspection of the prime mover and its auxiliaries at the end of each run. Also, road unavailability, based on experience, is about one-half that of diesels. This means better equipment utilization.

5. Less plant and property needed with electric.

Electric locomotives require fewer spare parts and do not require fueling or fuel-storage facilities. The consequent reduction in inventory is particularly evident when compared to the large investment in spare diesel parts, locomotives, and space required for storage and overhaul.

6. Maintenance expense of electrics is lower than diesels.

Because the straight electric locomotive is simpler (it has fewer moving parts), the maintenance and inspection downtime for each unit is less. When these factors per unit are added to fewer electric units required, the reduction in maintenance and inspection expense with the straight electric locomotive fleet is significant.

## IMPROVED SERVICE

If a complete changeover to an all-electric operation is effected, many other economic advantages will be realized.

1. Electrics are capable of higher speed on grades and consequently permit faster schedules.

The straight electric locomotive for a given weight has the ability to develop higher horsepower than a comparable-weight diesel-electric locomotive in the higher speed ranges.

Because of this higher horsepower (above 15 to 20 mph) it is capable of hauling heavier loads at higher speeds. This characteristic, and the fact that the straight electric is not limited by the output of an on-board prime mover, lead to greater rolling stock and track utilization for the same number of locomotive units.

2. Stocking and handling of fuel and crankcase oil will be substantially reduced with electrics.

Costs of handling and stocking fuel and crankcase oil are both significant and measurable. These economies are easily identified in a specific electrification study.

3. There are other advantages to which values cannot be as readily assigned but nonetheless are important and of value to the demands of modern transportation. Among these are the following:

Higher-speed passenger travel, including commuter service, will provide a clean, attractive travel mode reducing highway congestion. It has been calculated that seven four-lane highways are required to equal the traffic-handling ability of one two-track railroad. Here is economy of land use.

The electric locomotive's flexibility lends itself to tomorrow's needs in which automation will play a key role. The simplicity of the electric makes automation simpler. Complex diesel-engine speed-control devices are eliminated. This allows superior service reliability and an extended range of capabilities.

The electric locomotive operation is pollution-free and it is much quieter than the diesel-electric. Air pollution and noise levels are important considerations that will attract significant attention in this decade.

## CIVIC AND SOCIAL VALUE

An electrified railroad provides various civic and social benefits.

1. Railroad electrification provides cleaner, quieter, pollution-free operation.

Fuel-oil spillage and lubrication-oil disposal will be minimized, if not completely eliminated. These benefits and advantages contribute to the railroad's image and are consistent with national and local interest in environmental improvement.

2. Esthetics of railroad rights-of-way.

The opportunities inherent in utilizing the railroad right-of-way for combined utility transmission and railroad facilities could result in improved over-all community esthetics as well as economic benefits.

3. Electrics can provide a new image.

The future of transportation and the pace of change point in the direction of railroads carrying short-run, high-speed traffic. Railroads will take their proper place in the transportation world by complementing other modes. The electric locomotive is capable of filling the need of higher speeds to move people and goods faster. This presents the opportunity of a new, fresh image for the American railroad. The acceptance of the Metroliner in the Northeast Corridor, the Congress and Ryan Expressway Transit Lines, and the outstanding public acceptance of the Phila-Lindenwold High-Speed Line support this conclusion and will form the catalyst for a railroad renaissance.

# *Chapter 2* | Benefits to Electric Utilities

The previous chapter dealt with benefits to the railroad industry that would derive from railroad electrification. Equally important in establishing the over-all feasibility of electrified railways are the advantages and opportunities offered the electric utility industry. For, as much as any other factor, advances in electrified rail transport in this country will depend on its attractiveness to both industries—on being able to demonstrate that it is a sound business venture.

Utility benefits of railroad electrification relate directly to an opportunity for increased energy sales and revenue. Major emphasis in this chapter, therefore, is placed on an evaluation of the electrified railway market in terms of its size, characteristics, and specific potential for load growth and kilowatt-hour consumption. In addition, certain other less tangible but equally important advantages are identified and discussed.

## MARKET CONSIDERATIONS

As part of its over-all investigations, the Task Force assembled information dealing with the dimensions and characteristics of the railway electrification market. This, together with detailed load and energy use data obtained from Penn-Central operating experience, strongly suggests that, though in many respects unique, the railway electrification market presents electric utilities with a number of very interesting and attractive sales opportunities.

## SIZE OF MARKET

Electrified railways have been described as representing an energy market with a load growth potential second only in size to electric home heating. It has also been determined that one 6,000 rail hp electric locomotive annually consumes as much electricity as a subdivision of 1,000 all-electric homes. These two comparisons give some idea of the vast proportions of the railway electrification market.

In more specific terms, there are approximately 340,000 miles of rail track in the United States today. However, only a small percentage of this total—about 22,000 miles—has the traffic density which would support the investment necessary for electrification. Converting the estimated diesel-electric horsepower presently being utilized on these main lines into megawatts of electric utility load, a potential current gross market represented by electrified railways stands at about 3,000 megawatts. This is a somewhat conservative figure. Among the principal reasons for electrification are economy of operation and increased speed. Therefore, if existing trackage were electrified, horsepower and hence megawatts of load would undoubtedly be substantially higher.

## LOAD CHARACTERISTICS AND ENERGY SALES

Thorough analyses of electric load, demand, and energy consumption utilizing computer simulation of actual railroad operation on the Penn-Central Harmon to Cleveland route showed that:

> Kilowatt-hour consumption for the entire route was about 3 million kwhr per day or approximately 1.1 billion kwhr per year.
>
> Assuming a modest growth rate, this consumption is projected to increase by approximately 15 million kwhr annually during the next six years.
>
> Currently, energy requirements with electrification are a little more than 600,000 kwhr per track mile per year. Again, this is projected to increase to about 800,000 kwhr by 1975.
>
> From these findings, an estimate for electrified railway energy use is between 25 and 30 kwhr per 1,000 gross-ton miles hauled.

Though these data were derived from a specific rail route and do not necessarily apply across the board, they are considered to be representative and, therefore, usable in making broader estimates of the total market potential of railway electrification.

Considering, then, only the 22,000 miles of track presently in service that would economically justify electrification, the market for electric energy consumption was about 13 billion kwhr at the end of 1969, and will increase to almost 18 billion kwhr by 1975, allowing for a modest growth factor.

As with the load data presented above, these market estimates are conservative. Quite probably some rail routes may have greater traffic densities than the one utilized for this study. In that case, their energy consumption could be higher—say in the order of 1 million or more kwhr annually per track mile. Also, if the railroad industry can achieve the kind of growth it is looking for, future sales of kilowatt-hours for railway electrification could approach 20 to 25 billion yearly.

In many cases, the *quality* of the railway electrification market is as attractive as its quantity. On the Harmon to Cleveland route, despite considerable variance in the demand factors between individual supply stations, the annual system load factor was 74 percent based on a 30-minute demand interval. Further, the peak demands on this route would not in most cases coincide with the electric utilities' daily or power pool peak load periods.

## GROWTH POTENTIAL

With marketing innovations and improved service, rail transport in recent years has had a very healthy growth. In the seven-year period from 1961 through 1968, the railroads had a growth in traffic of 33 percent or an average of almost 5 percent per year.

Looking to the future, several factors would suggest that this kind of growth will be sustained or perhaps even accelerated. One is the railroad industry's continuing efforts to upgrade its service and strengthen its competitive position. Another is the general boom in transportation, from which the railroad industry is expected to benefit perhaps more than any other mode because of the rapid development of shipping container methods and the "land bridge" concept making U.S. railroads a transcontinental link for freight moving between the Orient and Europe.

The total transportation goods market in 1968 was 1,830 billion ton miles. Forecasts indicate this will increase to 3,000 billion ton miles by 1980. Currently, railroads carry about one-third of the goods transported or approximately 600 billion ton miles. Allowing for no increase in market share, the railroad industry will be handling 1 trillion ton miles of freight by 1980. With even modest success in capturing a larger share of the total goods transportation market, this figure would be substantially higher.

Of course, a complete appraisal of the future of the railroad industry should include the potential for passenger transport, the possibilities of which have yet to be thoroughly investigated. It is reasonable to assume, however, that the current need of this country's transportation system will demand the use of high-speed, short-haul ground mass transportation for passengers.

The railroad electrification market can, therefore, be looked upon as not only a stable source of sales and revenue for the electric utility industry, but also as a market with very encouraging growth potential.

## SOURCE OF ON-SITE POWER GENERATION

The railroad industry's role as a major producer of on-site or "private" electric power is often overlooked as a marketing factor.

It is estimated that there is 60 million hp in diesel-electric locomotives now in use in this country. This represents about 45,000 megawatts of generating capability, making the railroad industry the largest non-electric utility power producer in the United States. The kilowatt-hours generated by the railroads are equivalent to over one-half of all on-site "private" power produced annually.

Railroad electrification, therefore, offers the electric utility industry an unprecedented sales opportunity in the on-site power generation market—indeed a most enticing prospect and challenge.

## OTHER BENEFITS

Complementing the benefits for increased energy sales and revenue offered by railroad electrification are several other advantages difficult to measure in dollars and cents, but equally important.

### 1. Area Development

The greater economy and efficiency of electrified rail transport, and the fact that electrified railways are cleaner and quieter, would result in a vastly improved ground transportation system. This upgrading of land transport would be a significant factor in promoting the progress of areas served by electric utilities.

### 2. New Market Area

Electrification of rail lines represents an opportunity for the entire electric industry to "open up" a totally new market area. Of the four major competitive energy markets—lighting, stationary motors, heating, and transportation—electricity has captured lighting and for the most part stationary motors. The electric industry has likewise been successful in advancing the use of electric energy for process heating and in recent years has made great strides in moving into the comfort heating market for homes, business,

and industry. The only major market area that has not been significantly penetrated is transportation.

With railway electrification, electric utilities could move immediately into the transportation market on a meaningful scale, something that would have far-reaching effects.

## SUMMARY

In total, railway electrification offers a number of specific benefits to the electric utility industry:

1. The opportunity to serve a load currently amounting to about 3,000 megawatts.
2. An opportunity for increased energy sales of 18 to 20 billion kwhr per year with resultant revenue growth approaching *$200 million* or more.
3. An opportunity to acquire not only a stable new load, but one which has growth potential.
4. An opportunity to effect a major conversion of on-site, customer-owned generating facilities.
5. An opportunity to assist in the development of a transportation system that would contribute to service area growth and progress.
6. An opportunity to make significant penetration into a currently neglected market area.

# Chapter 3 | Rate and Financial Considerations

To quote a specific unit cost to supply propulsion power to any railroad in the U.S. is not possible due to varying conditions, policies, legal considerations, and other matters concerning costs, billing, and division of facilities ownership. However, this chapter will present thoughts and suggestions that will serve as guidelines to assist in estimating the cost of supplying power or in preparing a complete proposal for railroad propulsion power facilities. Included is a listing of pertinent items of cost and items that should be considered in setting up contractual agreements between utilities and railroads.

## RATES OR CHARGES

There are four major areas in which costs related to railroad supply are found and which should be recovered through a tariff so designed or applied:

1. Demand
   a. Must cover demand-related costs, including some type of minimum demand.
   b. Because of the nature of the railroad operation, consideration could be given to billing demand by some peak-averaging method.
   c. The service agreement would encompass one or more delivery points, rather than separate agreements relating to each point of delivery.
2. Energy
   a. Must cover energy-related costs.
   b. Provision for losses.
3. Utility facilities for the exclusive use of the subject purpose. This would include an item such as transmission lines.
4. Other
   a. Any costs not covered by either the demand or energy charge should be covered by a separately stated charge.
   b. Automatic or periodic adjustments to cover changes in costs such as fuel, labor, materials, services, taxes, and costs of money should be provided by appropriate adjustment provisions.

## COST ASSOCIATED WITH SPECIFIC FACILITIES

Certain facilities that are generally considered to be part of the customer's utilization system may be owned and/or financed by the utility. In this case it is suggested a separate charge be made to railroad. The following fall into this class:

1. Substation facilities, including transformation to catenary voltages and associated structures and equipment.
2. Catenary switching facilities.
3. Control facilities.
4. Catenary system and structures.

## CONTRACTUAL ARRANGEMENTS

1. Long-term agreement (20 years or more).
2. Appropriate cancellation provisions which may include:
   a. Provisions for recovery of investment in equipment rendered idle.
   b. Incidental expenses associated with cancellation, e.g., facilities removal costs.
3. Provisions to afford reduced power costs with improved load factor, power factor, and off-peak operation.
4. Compensation for incidental costs associated with facilities installation, such as relocation or shielding of communication lines, if not included in the over-all cost of the catenary.
5. Operation and maintenance of special facilities should be based on cost plus a fee.

6. Compensation for utility ownership costs associated with specific electrical facilities may be covered by separate agreement where appropriate.

## DIVERSITY

Diversity associated with railway propulsion service results from a somewhat different causation than it does in conventional electric utility service. Under the usual conditions of service both the source of supply and the loads served remain physically stationary. Diversity on this type of system is a direct function of differences in time of peak use of electricity by different customers. The significant difference in propulsion service is that the load is not stationary but is moving with time from substation to substation.

Because of the dissimilarity between railway propulsion power and the conventional concepts of utility service, the approach to pricing may be considered by many utilities as a departure from usual practice.

## LEGAL CONSIDERATIONS

Railroad representatives have indicated a desire to purchase electricity under a uniform pricing structure even when supplied by several utility systems. Since the cost of service can be different for each supplier because of variation in the number of points of supply, difference in utility system costs, and in the effective railroad load diversity, separate tariffs negotiated with a single railroad by individual suppliers may not be identical in structure or price level. On the other hand, any concerted action taken by several utilities to establish a uniform price structure might raise the basic question of anti-trust.

Because of anti-trust implications, any legal obstacle to the pricing provisions of any electrification study could be a roadblock of considerable magnitude. It is of fundamental importance to the ultimate success of the railroad electrification that positive action be taken to resolve the legal question in order to reach a solution of the uniform pricing question.

## SERVICE ARRANGEMENTS

There are at least two methods of providing electric service to railroads, which are listed below.

1. Service would be furnished by each supplying utility under individually negotiated contracts between the utility and the railroad. Each of these agreements presumably would reflect the economic effect of the number of delivery points and the diversity associated with the particular power system involved.

   Using this approach, the average price per kilowatt-hour would be high for systems with few delivery points and consequently very little diversity of load. For systems with many delivery points the diversity would be much greater and, accordingly, the average price would be lower.

An alternate to this plan would be for one company to act as collecting and disbursing agent. To spread the burden, this activity could be rotated among the utilities involved.

2. A separate organization would be formed which would buy from the supplying utilities and resell to the railroad under a uniform price structure regardless of point of delivery. Under this method, the contractual agreement between the resale corporation and the utilities would provide for sharing of the benefits of the total project diversity with each supplying company.

## COST OF POWER

As stated at the beginning of this chapter, it is not possible to quote a rate per kilowatt-hour that will apply universally in the U.S. In fact, there is some risk in mentioning a specified quantity, even though it is based on actual data as applied to a named set of conditions. Nonetheless, specific quantities will be given here with the expectation that they will serve as a guide for someone making an initial study of electrifying a mainline railroad.

For reasons given above, it was not possible for the Task Force to determine the cost to serve the former New York Central R. R. as discussed in Volume 2.

Based on an analysis of published tariffs, it appears a cost of power of from 8 to 10 mills could be assumed. This range agrees with a proposal recently made by a western utility to a railroad. This does not include charges for specific facilities as mentioned above.

## CATENARY

A major consideration in railroad electrification is the cost of installing the catenary which the railroads may want the utilities or a third party to finance. On the basis of an estimated catenary system cost of $55,000 per track mile and assuming a 15 to 20 percent carrying charge, the ownership cost would be $8,250 to $11,000 per track mile per year. At this magnitude, it is of economic significance comparable to the cost of power itself.

# Chapter 4 Determination of Demand and Energy

Determination of the demand and energy of an electrified railroad is a complex and time-consuming computation. Fortunately, computer programs have been developed which can convert railroad operating data to demand and energy requirements. Such programs consider the plan and profile of the railroad, schedules of train movements, tonnage hauled, speed, and distance. Operating practices and schedules based on the use of diesel locomotives in computing for electric operation will not produce optimum results. An entirely new schedule must be prepared recognizing the higher speeds attainable with electric operation, the reduced turnaround time, and the greater availability of locomotives and rolling stock. With these data, the computer program will determine the demand and energy by selected sections of track for the entire railroad operation. The program will total the power requirements in each section to determine the load on each substation.

The load on each railway substation is single phase and will cause unbalance on the utility system. The result appears as a voltage unbalance at the various supply points and as negative sequence currents in the generators. The recommended permissible amount of unbalance is 5 percent on smooth rotor generators and 3 percent voltage unbalance at supply points. The determination of negative phase sequence currents, which will appear on the various generators, can be calculated using techniques similar to those used for the usual determination of short circuit currents either by network analyzer or digital computer programs. The report of the New York Central Railroad Electrification Engineering Study Group, Volume 2 of this report, covers the determination of the voltage and current unbalances as well as the demand and energy quantities in detail.

In order to make a preliminary evaluation of the sales of energy to be realized by a railroad electrification project, it is possible to make an approximate estimate without the expensive or lengthy detailed study which would be required to design a proper supply system. A rule of thumb for an approximate estimate is that 28 kilowatt-hours are required per thousand gross-ton miles hauled, as stated in Chapter 5. This figure represents the power supply to the high-tension side of the railway transformer and includes losses in the transformation and catenary. The 28 kilowatt-hours per thousand gross-ton miles is an average figure. Although this number would increase for ascending grades, it will decrease for descending grades and will give a reasonably accurate estimate of the amount of sales to be anticipated from an electrification project.

# Chapter 5 Engineering and Technical Considerations

This chapter presents engineering study results and recommendations relating to supply of utility service for single-phase railroad propulsion loads. Although the study results and recommendations will not apply specifically to all railroad electrification situations or to all utility systems, they can serve as a guide for prospective railroad electrification projects.

Because of its recognized superiority for providing a most economical and suitable over-all system for railroad electrification, the high-voltage, commercial-frequency (60 Hz, 25 kv) system was selected by the Task Force as being most appropriate for mainline electrifications. Discussions with representatives of railroads, electrical manufacturers, and consulting engineers both in this country and abroad confirmed similar recommendations in the 1952 Battelle Report and in 1957 by the Association of American Railroads. Advantages of this system include: simplified substation facilities; the availability of adequate supply in many areas directly from the existing utility transmisson system; minimum weight overhead power delivery system; and minimum number of supply points.

The effect of single-phase loads on three-phase power systems was investigated in cooperation with representatives of the General Electric Company and Westinghouse Electric Corporation. The investigation found it to be practicable and feasible to supply these railroad loads, providing certain limitations and arrangements are followed. These results were further confirmed by studies associated with serving the Penn Central between New York and Cleveland and change-over of the existing electrification from 25 to 60 cycles.

The Task Force examined substation facilities, catenary voltages, methods of supply, voltage regulation requirements, reliability, and the design, construction, maintenance, and operation of catenary systems. A major portion of the investigations was carried out by the Task Force and the New York Central Railroad Electrification Engineering Study Group, with Gibbs and Hill, Inc., acting as consultant on the catenary system.

To assist in the preparation of a meaningful report the Task Force was of the opinion that a study based on data from a specific railroad system would be most helpful. Because of its high traffic density and operating speed, that portion of the former New York Central system between New York and Cleveland was selected as a model. An engineering study group comprised of utility and railroad representatives was established. The results of this analysis are given in the New York Central Railroad Study Group Report. (See Volume 2.)

## THE NEW YORK CENTRAL RAILROAD ELECTRIFICATION STUDY

### 1. Scope

Highlights of the New York Central Study Group Report are given below. For complete details the reader is referred to Volume 2. The report includes a study of:

a. Methods of supplying a railroad traction load, development of catenary designs and costs for a modern system capable of high-speed operations.

b. Effect of single-phase traction loads on electric supply systems.

c. Development of the expected electrical demand and energy requirements.

d. Effect of traction loads on railroad and common carrier communication systems.

### 2. Conclusions Regarding Equipment and Facilities

a. There are no insurmountable engineering problems associated with the use of commercial-frequency electricity for traction purposes.

b. The necessary equipment for such a system is either in general use now or is readily available.

c. There will be no adverse effects on the utility

power supply facilities through the use of a properly designed system.

d. Although a nominal voltage of 25 kv was chosen as the basis for this study, it appears that even higher voltages are realistic and may be more desirable under certain circumstances.

e. The installation of capacitors at trackside substations does not materially improve voltage regulation. If power factor correction is to be optimized, it should be accomplished at the locomotives.

f. The use of wood poles to support the catenary system may be possible where guying is not a problem. Based on utility experience, it would appear this type of construction would have an economic advantage over the self-supporting steel structures recommended in the Gibbs and Hill report (Volume 3).

g. For a small increase in cost (less than 1 percent) the catenary system could initially be made adequate for operation at 150 mph rather than 100 mph.

## 3. Discussion

a. *Locomotive Characteristics*

8,000-hp locomotives were selected to meet the railroad desire to purchase maximum horsepower in a single operating unit, and because a manufacturer indicated a locomotive of this size could be produced.

Typical freight trains were pulled by either one or two 8,000-hp locomotives.

While it is recognized that locomotive power factors vary with output, all study calculations were based on 90 percent power factor.

b. *Catenary Voltage*

A catenary voltage of 25 kv was selected. While a detailed analysis might indicate a voltage of 50 kv to be more economical, numerous bridges and other clearance restrictions associated with the selected railroad trackage would make the adoption of a higher catenary voltage difficult.

c. *Catenary Section Length*

An average section length of 20 miles was selected for initial evaluation purposes. Subsequent studies indicated this was a reasonable figure, with the actual section length averaging about 18.5 miles.

d. *Traffic Density*

Railroad traffic engineers indicated the maximum design density on any given section of catenary. In this case the design specification was three trains in an 18- to 20-mile section. It was further estimated that two of these trains would have one 8,000-hp locomotive and the third would have two 8,000-hp locomotives.

e. *System Design Voltages*

A nominal system design voltage of 26.5 kv was selected with a range of 29 to 20 kv. The minimum emergency level was designated as 20 kv.

f. *Catenary System Capacity and Characteristics*

The train data and emergency service conditions specified were analyzed through the use of a train performance program to determine the maximum catenary section load. Program results indicated a requirement for 1,250-amp catenary capability.

A center feed system was adopted using a 1,250-amp catenary which is load-limited rather than voltage-limited. (See Volume 2, page 50.)

The catenary system design consists of a constant-tension system with weathering steel supports located approximately every 230 feet. The messenger specified is 3/0, type EK, copperweld wire which supports a 300-mcm, standard ASTM, hard-drawn grooved copper trolley wire. One 300-mcm, ACSR return conductor is to be carried on the supports on each side of the tracks.

g. *Electric Supply System*

The electric supply system consists of 35 transformer substations and 35 switching substations. The supply substations are fed from lines of 115 kv or higher voltage.

In general, each station is equipped with one 20-mva transformer with provision for a second. Volume 2, pages 54 and 55, illustrate the single-line diagram and plot plan of a typical transformer station.

A switching station was placed between each two substations with the required circuit breakers and associated equipment. (See Volume 2, page 51.)

The normal mode of the system operation is illustrated at the top of page 51, Volume 2, where the shaded blocks indicate closed breakers.

In the event of a supply failure, the switching sequence would be to open the breakers fed by that station and close the breakers in the adjacent switching stations which are connected to the same catenary as illustrated at the bottom of page 51, Volume 2. This will increase the length of catenary fed by each of these two stations to approximately 30 miles.

The railroad may select either automatic or manual control for this switching, but fault-clearing operations must be fully automatic.

h. *System Costs*

The cost of electrifying the prototype railroad from Harmon to Cleveland is estimated to be about $100,800,000. This includes the catenary system for

1,485 track miles at $86,200,000 and 70 wayside substations at $14,600,000. The cost to extend the power system transmission line facilities to reach the wayside transformer substations is estimated at approximately $6,600,000. These estimates are based on 1968 price levels and take into account the physical conditions encountered in the territory involved.

The estimates should be used only as guides since local conditions can produce substantially different values. For example, the average cost per track mile from the above is $58,000 but if the two highest cost areas, where the terrain is very unusual, are deducted, the average becomes $52,000. Further, if the average man-hour rate of $12.50 used in the study were reduced to $10.00, the average cost per track mile of catenary would be further reduced to $47,300. Included in the catenary estimates is 18 percent for engineering and construction management.

i. *Load Data and Characteristics*

The study was based on 1965 railroad operating data with an assumed annual growth factor which produced an average daily traffic volume of 116,000,000 GTM in 1975. It was recognized by the Study Group that the load characteristics of true electrified operation would not be the same as merely using diesel operation and converting horsepower to kilowatts. The NYCRR prepared schedules and other operating data for the year 1965 to recognize the increased speed, decreased turn-around time, and other data for the year 1965 and other advantages of electric operation, and these data were used in the General Electric Company computer program. Based on the 1965 data, an annual energy consumption of nearly one billion kwhr with a 15-minute demand of about 150 mw at 68 percent power factor was determined for an average daily traffic of 82,900,000 GTM. This is equivalent to 28 kwhr sold per 1,000 GTM, a figure substantiated by experience on the present Penn-Central electrification.

Railroad operation produces a fluctuating load. This is understandable when consideration is given to the fact that trains start and stop, run fast and slow, and climb and descend grades. For example, the 15-minute demand of 150 mw becomes 160 mw on a 3-minute basis, and 145 mw on a 30-minute basis.

The over-all load factor of the model electrified railroad averages 74 percent, which would be that presented to the interconnected systems supplying it; however, the load factor on any individual substation could be as low as 10 percent. Although individual substation load factors are used in design, the effect of generation on the interconnected utility systems is the railroad demand as a whole. A load of 150 mw, using a billion kwhr per year at about 70 percent power factor and a 74 percent load factor is as good as, if not better than, most industrial loads.

## POWER SUPPLY SYSTEMS

Service to large, single-phase, commercial-frequency railroad loads may present a number of engineering problems which must be recognized and evaluated to insure that system performance will remain within tolerable limits and that no adverse effects will result. To adequately supply single-phase railway loads, the supply system must have capability to absorb significant amounts of unbalanced loading and load variation.

### 1. Effect of Single-Phase Load on a Three-Phase Power System

a. *Phase Current Unbalance*

The single-phase railroad load causes negative sequence currents to flow in the generators and to a greater degree on the particular line or lines from which the single-phase load is fed. The amount of negative sequence load which a generator is capable of carrying is principally a function of heating of the slot wedges and rotor body ends.

The negative sequence currents would appear in varying amounts on individual generators, those electrically closest to the supply points being subjected to the larger amount of unbalance. Two major American equipment manufacturers have published data indicating that, at rated voltage and rated load, generators are capable of carrying 5 percent negative phase sequence current continuously.[1, 2*]

British and Japanese designs permit up to 10 percent negative sequence current, although in neither country has the railroad unbalanced loading exceeded 5 percent.[3] While the actual limits should be obtained from the manufacturer, in general it appears that a generator can carry about 5 percent negative sequence current.

b. *Voltage Unbalance*

Single-phase load applied to a transmission system will cause an unbalanced voltage to be imposed on other equipment supplied from the same source. The effect is most troublesome to polyphase motors, causing overheating quantitatively expressed by the relation

$$H = 2V^2$$

where

$H$ = temperature rise on the unbalanced phase above the other two in percent

$V$ = percent voltage unbalanced

Using this relation, a 3 percent voltage unbalance would cause 18 percent higher temperature in the unbalanced phase, which will raise the entire motor

*See Bibliography, page 16 of Volume 1, for numbered references.

temperature about 6 percent. Although NEMA standards for motors give no permissible unbalance figure, it is generally recognized that a 5 percent unbalance is satisfactory. Again, the British and Japanese practices recognize that 5 percent can be tolerated by motors but have limited the voltage unbalance caused by single-phase railroad load to 3 percent. It is recommended that a 3 percent limit be adopted in this case, since no harmful effects have been noted at this value or below.

The amount of unbalance can be determined by the relation

$$C = \frac{L}{S} \times 100$$

when

$C$ = percent unbalanced voltage

$L$ = single-phase load, mva

$S$ = three-phase short circuit capability, mva

Assuming a value of 3 percent for $C$, a 20-mva, single-phase railroad load could be carried by a substation where the short-circuit duties are 667 mva.

c. *Sudden Load Impact*

In general, the system strength required to overcome the voltage unbalance will also provide for the sudden load impact. Also, careful attention to the catenary phase break design and operation of locomotive controls, when passing through a phase break, may ease the problem.

## 2. Railroad Load Characteristics

a. *Power Factor*

The power factor is principally a phase distortion effect produced by the firing angle of the locomotive rectifiers, rather than an inductive effect. Experience indicates this to be between 82 and 88 percent.

b. *Harmonics*

Rectifier-type motive power produces harmonics which are reflected back into the utility system. Electric locomotives are in operation today using this principle on 25-cycle systems. Tests on them constitute most of the available data on large, single-phase rectifiers and indicate the harmonic content is less than 6 percent. From the analysis of these locomotives and from the experience in France and Britain, the harmonics are of a minor nature and are effectively reduced by natural system capacitance to a point where they do not cause overheating of motors or other apparatus.

c. *Inductive Interference*

The load current in the trolley is returned to the supply via the running rails and constitutes a source of inductive interference in paralleling communication circuits. This is further aggravated by the harmonics, as well as the fact that part of the rail current will return through the earth. In a report to Committee 13, Electrical Section of the Association of American Railroads, 1958, an analysis of inductive coordination of a 60-cycle railroad was made and it was concluded that the inductive coordination problems introduced by the 25-kv, 60-cycle systems are no more serious than those experienced by electrification projects in the past. This finding was confirmed by a Bell Telephone Laboratories study conducted in 1967.[4]

d. *Radio Interference*

Radio interference may be anticipated from two sources—the arcing of the pantograph on the contact wire, and from corona, particularly with a catenary operating at 50 kv.

The corona problem may be aggravated by the numerous small cross-section hangers, and sharp-edged fittings associated with catenary hardware. This is an area where detailed testing and investigation appear desirable at any voltage.

A properly designed catenary system should limit arcing to a sufficiently low intermittent level that complaints will not occur. This is confirmed by European and U.S. experience on existing systems.

e. *Cathodic Protection*

The ground return currents associated with single-phase railroad loads will affect the existing ground potential along the railroad right-of-way. This current will necessitate examination of the cathodic protection systems associated with existing underground metallic structures.

# THE RAILROAD POWER DELIVERY SYSTEM

The power delivery system, comprising the substations, switching facilities, and overhead power delivery or catenary system, represents the largest component of railroad electrification capital investment and an area of primary interest to supply utilities. The mechanical properties of the catenary system determine the speed of operation, and the electrical characteristics may dictate the substation spacings and demands which can be supplied to meet railroad operating requirements.

## 1. Catenary Voltage

The characteristics of the railroad's power demands and line clearances associated with bridges and tunnels indicate that three catenary voltages may be desirable to meet the varying requirements of America's railroads.

In areas with only a limited number of overhead

clearance restrictions and trains presenting high electrical demands, a 50-kv catenary voltage appears economical and desirable. The higher voltage will permit longer catenary sections, fewer substations, and a lighter catenary system. Because of the larger section of electrification which can be covered at 50 kv, in most cases some improvement in supply point load factor and power factor may be anticipated.

It appears that 50 kv may prove to be the most economical voltage for a large number of North American railroad electrifications. Currently, two major western railroad electrification studies have confirmed that 50 kv is the most economical choice in these cases.

Locomotive manufacturers indicate that 50-kv locomotives can be built for only a slight increase in cost (less than 5 percent) over 25 kv.

In areas having large numbers of overhead bridges, tunnels, and other structures requiring major engineering expenditures for increased clearance, 25 kv may be the only voltage that can feasibly be employed. The existence of certain major tunnels indicates that the use of 12.5 kv will be necessary in a few instances where it may not be economically feasible to obtain additional clearance.

Locomotive manufacturers indicate that it will be possible to construct equipment capable of operating on two or more of the indicated voltages. It must be recognized that such locomotives will be more costly and complex; therefore, when possible, a single voltage should be adopted.

## 2. Methods of Supply

The center feed system in which each transformer substation feeds into the center of a catenary section and is isolated from the adjacent supply substations is suggested. This method of supply is illustrated in Volume 2, page 54.

The center feed system avoids the establishment of a tie between two points on the utility system via the catenary system. Such a tie can cause an unwanted diversion of current from utility lines and overload the railroad power delivery system. This would be most serious when parallel utility facilities are out of service.

Switching stations mid-way between supply substations offer an opportunity to bring the catenaries of every track through individual switches onto a bus. This will reduce impedance values substantially and may permit reducing the size of catenary wire.

An alternative method of supply is the double feed system in which the substations are in parallel at each end of a catenary section. This method has the advantage of reducing catenary voltage drop, line loading, and losses. Where heavy grades or traffic conditions require exceptional catenary capacity and if no utility system problems are associated with its service, the double feed or parallel method may prove to be the most desirable choice.

## 3. Wayside Substations

Transformer size is determined by the load in the catenary section supplied. Based on preliminary studies, it appears that a capacity range of 20 to 40 mva will be required, depending on the catenary voltage and capability of the power system.

## 4. Reliability

Railroads generally can tolerate interruptions of short duration (up to 60 seconds); this will permit operation of motor-operated air break switches without adverse effects. Therefore, in most cases, automatic air break switch sectionalizing will provide an adequate quality of service.

Two-way transmission service to all substations is desirable, but if the railroad is designed to operate with one transformer substation out of service, radial supply lines may be acceptable.

## 5. Voltage Regulation

In most areas of the United States, the utility transmission system voltage regulation is within tolerable limits for railroad service requirements; therefore, LTC transformers will not be required.

It is recommended the utility industry urge a locomotive design be adopted for +10 percent to –25 percent voltage range as minimum acceptable limits.

## 6. Signal and Communication System Changes

The signal and communication system changes associated with electrification are a major cost item. Present estimates for installing a system which is not influenced by the rail ground return currents and inductive interference are in the range of $25,000 to $35,000 per track mile. It is possible that systems under development might reduce this to $1,000 to $20,000 per track mile. This is an area in which further research and engineering development is required.

## 7. Clearances to Structures and Equipment

The Association of American Railroads 1959 manual recommends a minimum 10-inch clearance for 25 kv.

A task force of the American Railway Engineering

Association is currently working on the development of recommended clearances for 12.5 kv, 25 kv, and 50-kv overhead power delivery systems.

The 25-kv clearances currently used in Europe are as follows:

UIC: 11 inches static; 8 inches passing (to be revised)

British Railways: 8 inches static; 6 inches passing

## 8. Catenary Design, Construction, Maintenance, and Operation

Catenary systems are covered in considerable detail in the Gibbs and Hill report (Volume 3) mentioned earlier.

It appears that a weight-tensioned system employing a hard-drawn copper contact wire, and other components of copper, copperweld, or stainless steel is most commonly used. While not yet used on a significant scale, ACSR may be used in place of a copper or copperweld messenger.

While additional cost and complexity are associated with a weight-tensioned system, it provides significantly better pantograph tracking and is recommended for all installations where speeds greater than 40 to 50 mph are anticipated.

## 9. Catenary System Life

Railroad experience indicates that the catenary installation has a 50-year or more life expectancy. Because of the effects which arcing and current transfer density have on contact wire, annealing, and burning, plus the differing wear rates associated with various types of pantograph running strips, the utilities must be concerned with the pantograph design in the event that the catenary is utility-owned.

# Chapter 6 | Suggestions for Future Activity and Research

If railroad electrification is to move ahead, there will need to be joint activity among interested utilities, railroads, manufacturers, consulting firms, and government agencies. The Edison Electric Institute, the Association of American Railroads, and the U.S. Department of Transportation are, together, in an unusually advantageous position to show leadership toward their goal. There is an immediate need for development of background information, data on equipment characteristics, engineering designs and the other elements necessary to the next stage in railroad electrification.

With this in mind, the EEI Task Force on Railroad Electrification suggests that a joint meeting be held promptly at which representatives of these three organizations may explore such matters of mutual interest as:

- Possible joint use of rights of way and structures.
- Catenary system design and standards.
- Information compilation and distribution.
- Economic evaluation of railroad electrification.
- Possible innovations in capital costs of railroad electrification.
- Economic evaluation of high speeds, greater acceleration, and other benefits associated with electrified operation.
- Possible areas for joint research.
- Legal and regulatory matters.

The Task Force also recommends that consideration be given to the development of a utility-supported publicity campaign in both specialized railroad and utility trade publications, and in selected general news magazines, in order to develop awareness of electrification advantages among railroad managements, railroad stockholders, government officials, investors, and the general public.

The railroads and the utilities have a responsibility to consider foreign suppliers and their techniques. At the same time, all interested parties have a responsibility to assist in the standardization of components. The Task Force recommends that appropriate attention be given to these subjects.

Equipment suppliers and consulting engineering firms must work together with the railroads and utilities if railroad electrification is to be advanced. The development of the best techniques and the most economical systems in the initial stages of railroad electrification will be of long-range benefit to all parties. The Task Force notes that areas requiring significant additional research and development include catenary system masts, hardware conductors, fabrication and erection, railroad signal systems, and possibly motive power. In many cases, acceptable equipment is available, but it appears that significant cost reductions might be achieved by the use of new materials or the development of improved fabrication and erection techniques. The Task Force urges equipment suppliers and consulting engineers to give prompt attention to these areas.

The large-scale electrification of America's mainline railroads will involve decisions from government bodies and agencies on Federal, state, and local levels. There are difficult questions to be faced involving tax treatment of catenary facilities, utility rate problems, urban zoning, and a variety of other legal and regulatory matters. The Task Force suggests that the Department of Transportation study these areas and suggest solutions to the problems involved. The Task Force itself stands ready to aid in this activity on request of the EEI Committee on Railroad Electrification and the Department of Transportation.

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